ONSET OF MOTION AND DEPINNING OF A BRAGG GLASS

Guohong Li and Eva Y. Andrei

Department of Physics and Astronomy,Rutgers University
Piscataway, New Jersey 08855, USA

P. Shuk and M. Greenblatt

Department of Chemistry, Rutgers University
Piscataway, New Jersey 08855, USA

1. INTRODUCTION

The response of vortices to applied currents or fields has been a topic of intense study for almost half a century. Surprisingly, in spite of enormous progress in our understanding of vortex physics, many of the outstanding questions identified by Anderson and Kim in 1964, are still unsolved[1]. Their statement " we have made no progress in studying the transient solutions ... when one quickly applies an external field or currents to a superconductor" is still valid today. Most experimental studies on the dynamics of vortices have focused on the evolution of the magnetization to an applied field in the limit of long time scales[2-4]. The much faster initial transients occurring in magnetization experiments have received less attention. Similarly few experiments have focused on the response of a superconductor to a suddenly applied current.

Standard transport experiments measuring the steady state response to an applied current provide information on the degree of order of the vortex state. For clean samples where pinning is absent vortices are expected to form an ordered state, the Abrikosov lattice[5] at low temperatures and fields. Pinning arising in the presence of any amount of material defects destroys the long-range order[6] of the vortex lattice. In the limit of weak pinning however, the Abrikosov lattice can maintain its topological integrity, forming a so-called Bragg glass [7-12] with quasi long-range order. As thermal fluctuations or the strength of pinning are increased, the Bragg glass undergoes a transition into a less ordered liquid or glassy state. As shown by Pippard [13] and Larkin- Ovchinninkov[14], the transport signature of this transition is an increase in the critical current density, $J \propto R_c^{-1/2}$ where R_c is the size of a coherent Larkin domain[6]. This may be the origin of the peak effect, a sharp rise in critical current observed just below the superconducting transition in weak pinning superconductors[15,16].

The critical current I_c is determined from standard transport measurements as the current for which a small longitudinal voltage drop, typically $1\mu V$, is detected. The voltage drop signals the onset of vortex motion and the loss of superconductivity. The temperature and field dependence of I_c contain information on the collective properties of the vortex lattice. Further information on the vortex dynamics is gained from the shape of the $V(I)$ curves. If in response to the applied current I,the vortices move uniformly, the voltage $V = \rho_{ff}(I - I_c)$ is linear in the applied current with $\rho_{ff} = \rho_n H/H_{c2}$, H the applied field, H_{c2} the upper critical field and ρ_n the normal state resistivity. This regime known as free flux flow is generally expected at high current levels. The situation is more complex close to I_c at the onset of vortex motion where the $V(I)$ is non-linear. Various models have been developed to describe this onset in term of thermal activation across bulk pinning barriers[1-3,17,18]. Recently it was shown that in clean $NbSe_2$ samples the non- linear $V(I)$ are a result of the surface rather than bulk barriers[19,20]. The surface barrier inhibits vortex motion in and out of the sample and causes a non-uniform distribution of the transport current due to the excess force needed to introduce vortices into the sample [21]. By separating the contributions of surface and bulk to the $V(I)$ characteristics these experiments demonstrated that thermal activation across the surface barrier is the sole origin of non linearity while the bulk contribution remains linear down to the experimental resolution.

Going beyond the steady state $V(I)$ characteristics, pulsed transport measurement [22, 23] revealed rich dynamics in the vortex response near the peak effect. These experiments showed strong metastabillity, nonlinear dynamics and clear evidence of reordering in the vortex state resulting from its motion and from its interaction with boundaries. Below the peak effect transport measurements on a field cooled (FC) vortex lattice revealed that the FC state is metastable and that it decays to a stable state if perturbed by an applied current, a change in field or mechanically. The resulting stable state had a lower I_c which was close to that of the ZFC (Zero Field Cooled) state. These results were interpreted in terms of a supercooled disordered state that reorganizes into a more ordered state or Bragg glass when driven by a current[24,26].

Here we describe time resolved transport measurements that probe the response of the vortex lattice in $NbSe_2$ samples to an applied current pulse over a wide range of fields and temperatures. The response was characterized by two quantities: asymptotic voltage V_0 and rise time τ. We identified a region of the phase diagram where τ depends only on the asymptotic vortex velocity, derived from V_0. Despite the fact that pinning, vortex-vortex interactions and temperature varied the rise time remained the same if the velocity was sufficiently high. The region of phase diagram where this universal behavior is present coincides with that of the Bragg glass state identified in other experiments. This unique feature disappears when the Bragg glass becomes unstable at high temperatures or magnetic fields.

2. EXPERIMENTS

A pure single crystal of 2H-$NbSe_2$ (4.41 mm x 0.83 mm x 6 μm) was used

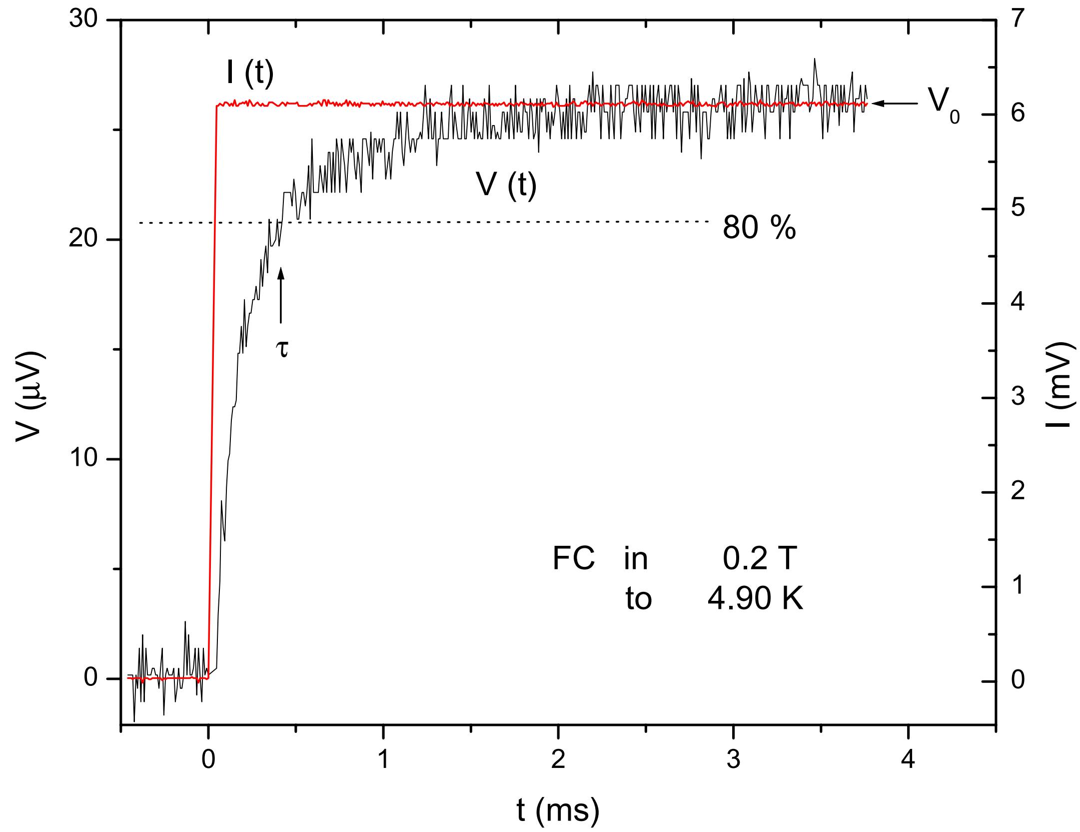

Figure 1. Response to transport current pulse. The vortex state was prepared by field-cooling. Definitions of the asymptotic voltage V_0 and the rise time τ are shown.

in this study. The thin platelet sample has a T_c of 7.2 K with a width of 130 mK in zero magnetic field. Standard four probe technique was employed in the pulsed measurements. The contacts were prepared by depositing Au/Ti film on cleaved sample surface, and the distance between voltage contacts was 3.43 mm. The magnetic field were applied along the c-axis, and currents were in the a-b plane. An external measurement and control system, Adwin-Gold was used for the pulse experiments because of its fast data acquisition and deep memory. Its analog output generated the current pulse and its analog input collected the response of the sample. The voltage response was amplified by a low noise fast amplifier before it was passed to the Adwin-Gold. For low level experiments, a Keithley 2400 source-meter and 2182 nanovoltmeter were used in order to increase the sensitivity.

In this paper we focus on the field-cooled (FC) vortex states whereby the sample is cooled below the superconducting transition in the presence of a constant magnetic field. The field was generated by a superoconducting magnet working in persistent mode. The sample was first warmed up into its normal state and then slowly cooled down to a temperature where the pulsed measurement was made. A low temperature response curve is shown in Fig.1. No voltage was detectable when the current is just turned on. This feature is typical for the low temperature data. At higher temperatures, above the peak effect the initial response is finite. With time the voltage increases gradually toward an asymptotic value V_0. The rise time τ is defined as the time to reach 80% of the asymptotic value. Similar response curves to a current pulse [25, 26] were seen in previous measurements.

3. RESULTS

The temperature dependence of the response to transport current pulses is shown in Fig. 2. Every data point was taken on a freshly prepared FC vortex state as described above. The vortex response is characterized by two quantities, V_0 and τ. Both are strong functions of the current pulse level I. The voltage current characteristics $V_0(I)$ obtained from the asymptotic response to pulses of varying amplitude coincides with the conventional $V(I)$ obtained in a standard slow transport measurement. V_0 increased linearly with I at high levels, and the slope is consistent with the free flux flow resistance. We note some rounding of the $V_0(I)$ at low levels close to the critical currents, which could reflect thermal activation over bulk barriers (creep) [1- 3]or over a surface the barrier [21]. The rise time τ increases sharply with decreasing I, consistent with previous studies [25, 26]. Both $V_0(I)$ and $\tau(I)$ depend on temperature for a given magnetic field as shown in the figure. This is not surprising in view of the fact that the competition between vortex-vortex interactions, pinning strength, surface barrier and thermal fluctuations ultimately determines not only the vortex state but also the dynamics. However what *is* surprising is the fact that the temperature dependence disappears when plotting τ versus V_0. In other words in this regime the rise time τ is determined by the asymptotic voltage V_0 alone, and is insensitive to applied current or temperature.

The results of the same experiment carried out in different magnetic fields are shown in Fig. 3. Here again we note that $\tau(V_0)$ is independent of temperature but does depend on the value of the magnetic field. If the curves at various fields represent the same physical phenomenon it should be possible to obtain a further collapse by plotting the response in terms of intrinsic physical parameters. Clearly τ is intrinsic to the dynamics and so is the velocity v, but the voltage $V_0 \sim nv$ is not because it depends on the density of moving vortices n which varies with field. We therefore plot τ against the vortex velocity $v \propto V_o/B$ in the lower panel of Fig. 3. We find that the entire data set collapses onto a single curve that corresponds to a power law curve $\tau \propto v^{-3/2}$. This simple law holds at high vortex velocities over a range of temperature and fields. At low velocities, deviations appear [27] (hints of the deviation can also be seen in Fig. 3). The fact that this universal behavior holds over a wide range of velocities, fields and temperatures is even more remarkable in view of the fact that in the same regime the critical current depends strongly on field and temperature.

Of course this universality cannot persist throughout the entire phase space. To study the region of phase space where this behavior holds we repeated the experiments over a range of fields and temperatures. In Fig. 4 we display the field and temperature dependence of the rise time corresponding to the same asymptotic vortex velocity, $36mm/s$. Note that in order to drive the vortices toward the same asymptotic velocity the driving currents, which have strong field and temperature dependence, had to be adjusted accordingly. The universal behavior shown above is evident here for a range of fields and temperatures where $\tau = 0.6ms$. Beyond this regime as the field or temperature are increased we note a sharp drop in τ. The onset temperature of this drop is quite well defined since it is almost independent of the vortex velocity. In fact, the whole τ(v) curve shifts downward at this temperature (data not shown here).

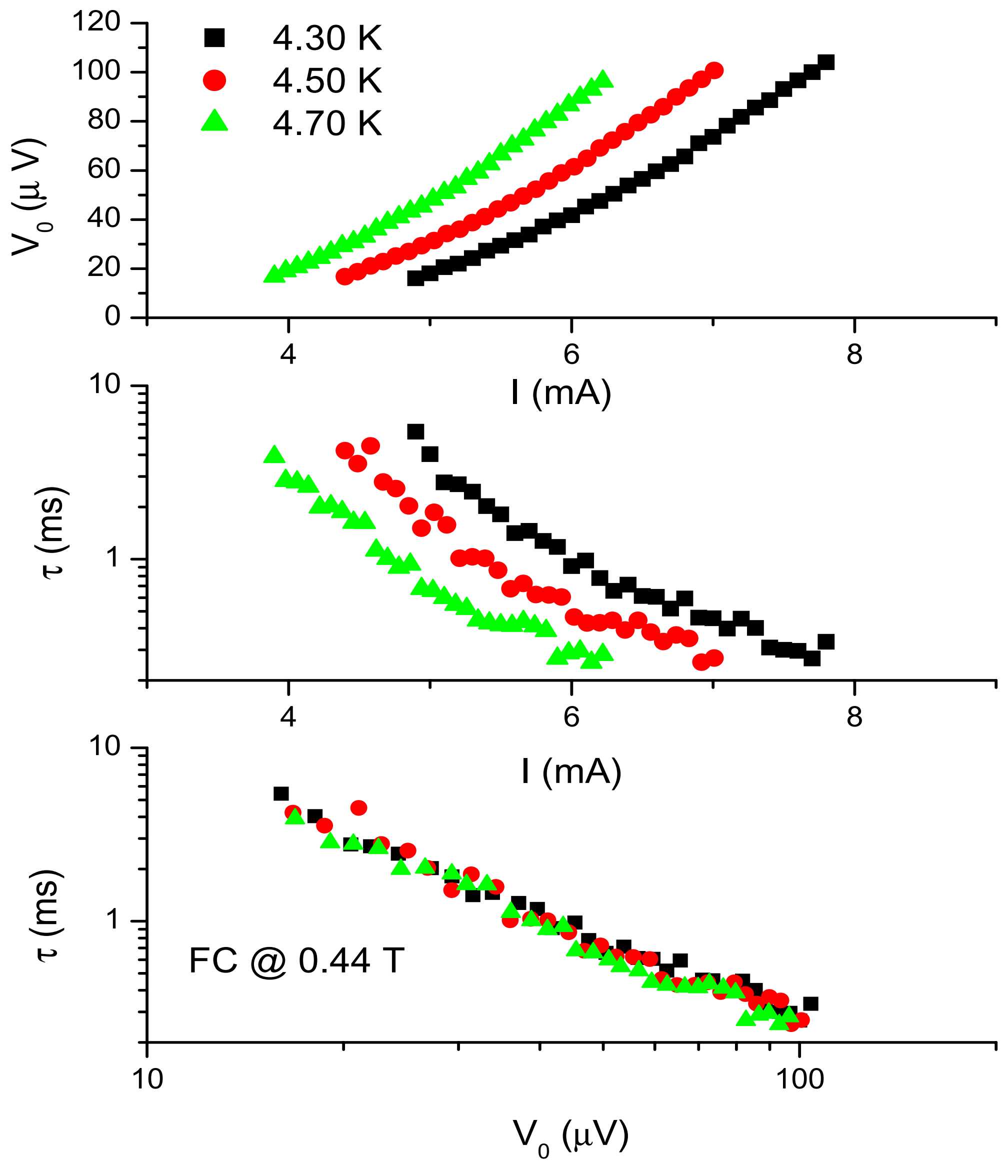

Figure 2. (top) Asymptotic voltage versus current pulse level at various temperatures. (middle) Rise time versus current pulse level at various temperatures. (bottom) Curves of asymptotic voltage versus rise time for various temperatures collapse onto the same line. No adjustable parameters or normalization were used.

In Figure 5 we plot the vortex phase diagram. In addition to the usual lines representing the upper critical field H_{c2}, the positions of the peak H_p and the onset of the peak effect H_o we show the region of the phase space where the measured $\tau(v)$ is independent of field and temperature by hatched bars. The boundary of the regime where this new dynamic behavior is observed coincides with that of a stable Bragg glass (to be published elsewhere) shown by the dotted line in Fig. 5.

4. DISCUSSION

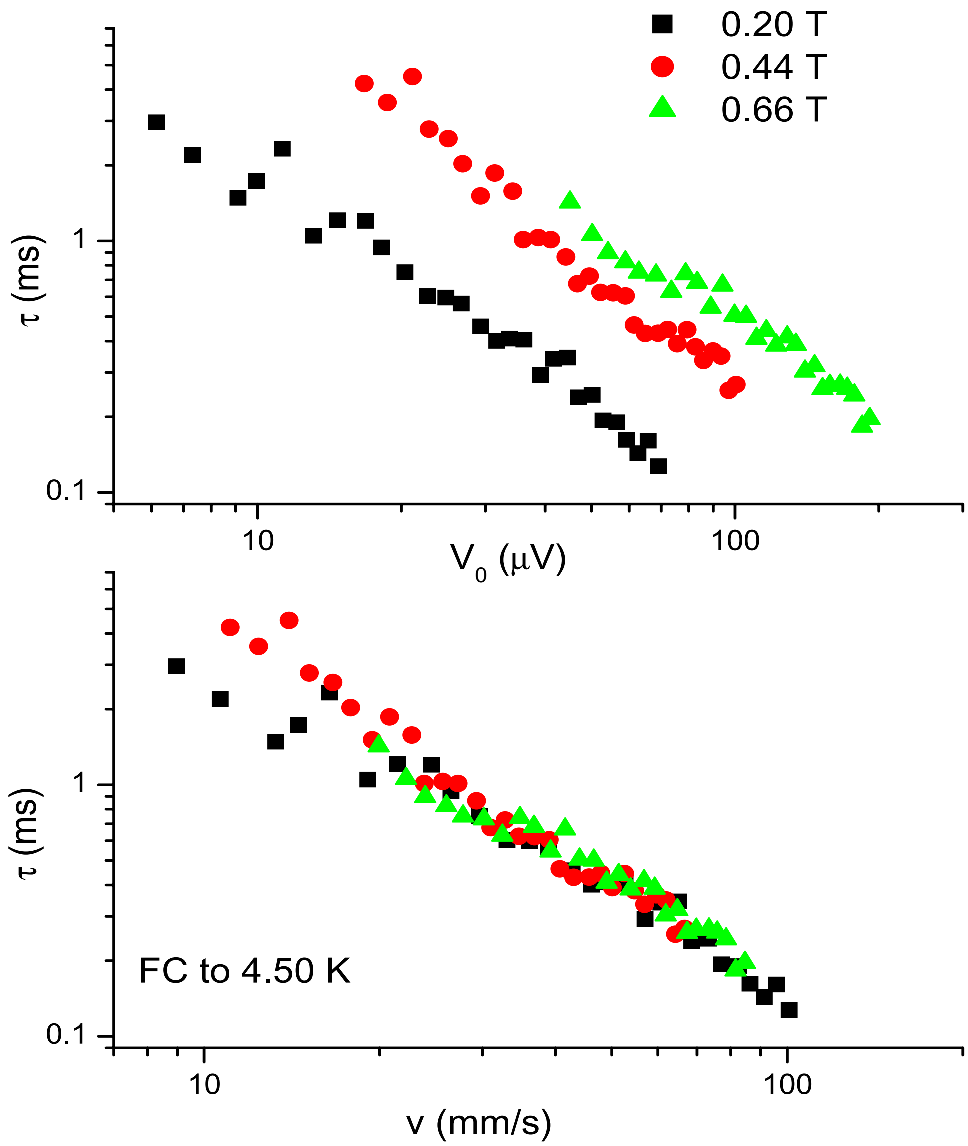

Figure 3. Rise time dependence on asymptotic voltage for three values of magnetic field (top) collapse onto the same line when the rise time is plotted against the vortex velocity (bottom).

We now discuss possible origins of the rise time in the regime where it is uniquely described by the asymptotic velocity.

a. The inertial mass of vortices contributes little to τ because it is too small [28-30].

b. Thermal activation above a pinning barrier is commonly associated with long logarithmic response times in magnetization experiments arising from vortex creep. But the response times of vortex creep are strongly temperature and field dependent. By contrast in the regime described here low temperatures, low fields and free flux flow - the response time is independent of temperature.

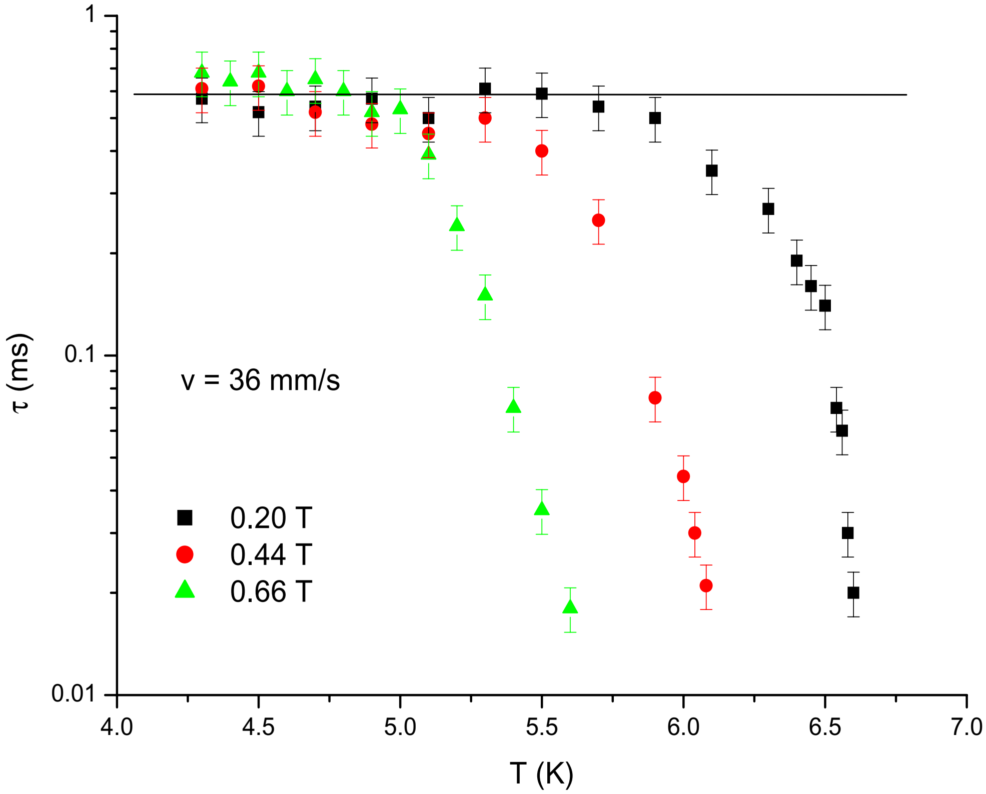

Figure 4. Temperature dependence of the rise time τ for vortices driven toward the same asymptotic velocity, 36 mm/s by a current pulse. At the lowest temperatures τ is uniquely defined by the asymptotic velocity.

c. Thermo-magnetic instability. Experiments following the vortex motion in response to an intense laser pulse [31] or to a small applied field [32-34] in thin superconducting film showed that the response is dominated by a thermo-magnetic instability which gives rise to field penetration into the sample via dendritic growth patterns. Within the dendritic regions the vortex lattice was found to be in a disordered or liquid state. The thermo-magnetic instability was not observed for thick samples or in large magnetic fields exceeding several Gauss. Since the samples used in our experiments were thick ($> 6\mu m$) and the fields large ($> 0.1T$) it is unlikely that this instability is responsible for the observed behavior.

d. Establishment of field gradient. Current penetration into the superconducting sample requires a simultaneous rearrangement of vortices according to $\nabla \times H \propto J$. Therefore, when a current pulse is applied to an FC state, the initial flat vortex density profile has to evolve in order to produce a density gradient consistent with the applied current. The final density gradient is proportional to the asymptotic vortex velocity. In a sense the approach to the asymptotic velocity resembles that of a self organized critical state[35]. These systems reach the critical state through a succession of avalanches generated by a redistribution of energy between moving particles and their neighbors. Such mechanism quite naturally can result in a power law dependence of the rise time on the asymptotic velocity. The dynamics of self organized criticality could take place in a vortex system if the energy of moving vortices is shared with neighboring vortices faster than it is lost to the environment.

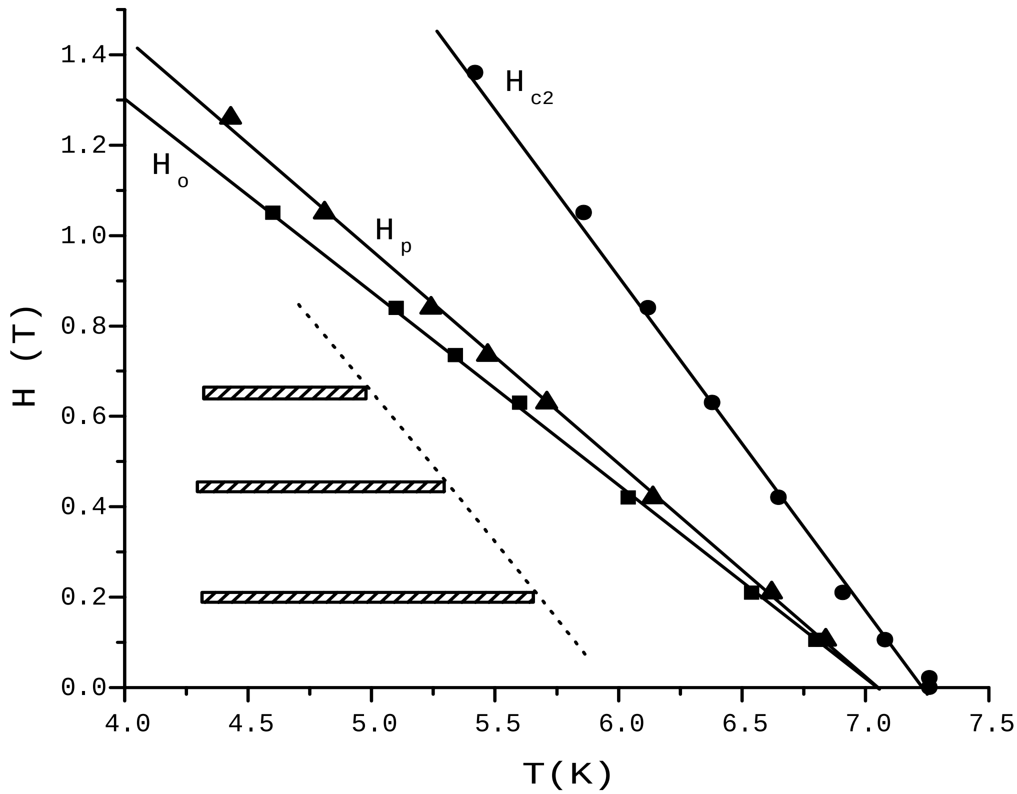

Figure 5. Vortex phase diagram for NbSe2. The upper critical field line H_{c2} separates the normal from the superconducting state. The peak effect is marked by the onset H_o and the peak H_p. The hatched bars represent the region in phase space were the response to a current pulse is uniquely defined by the asymptotic vortex velocity as seen in Fig. 3. The Bragg glass can be reached by field-cooling at temperatures lower than the dotted line (to be published). The solid lines are guides to the eye.

This would require a fairly coherent vortex lattice were the motion occurs in chunks rather than individual vortices or interstitials. In the Bragg glass regime were it is energetically unfavorable to form vacancies or interstitial that could facilitate sliding of individual vortices or small bundles these conditions are satisfied. By contrast outside the Bragg glass regime were vortex motion is less correlated the dynamics is governed by single vortex motion where the times scales are too fast to be measurable in our experiments.

e. Vortex reorganization. Rearrangement of the vortex lattice leading to a change in the critical current or a change in the number or distribution of moving vortices gives rise to a change in the voltage response. If the rearrangements occur within the experimental time scales they will naturally result in an evolution of the response to an applied current. Current induced rearrangements of the FC vortex lattice from a disordered metastable state to an ordered stable state with a lower critical current were previously reported in this system[24- 26] as well as in high T_c samples[36]. These rearrangements from a disordered to an ordered lattice can delay the current penetration into the sample if the rearrangement times are slower than the dynamic penetration times discussed in (d). In this case the local current density would initially correspond to the disordered state. As rearrangements occur throughout the sample reducing the value of the local critical current density the voltage response would grow until the entire sample is in the ordered state. The strong correlation between the reordering time and the asymptotic velocity observed at low fields and temperatures is a new and intriguing feature that could be a dynamic signature of the moving Bragg glass[27,37-39].

5. CONCLUSIONS

We have described a series of pulsed transport measurements to study vortex dynamics of over a wide range of temperature and magnetic field. Our experiments revealed that the two aspects of the response, asymptotic vortex velocity and the rise time are strongly correlated to each other in a region of phase diagram that coincides with the Bragg glass. Outside this region the response develops a strong dependence on field and temperature and can no longer be uniquely characterized by the asymptotic velocity. Our results strongly suggest that this novel feature is a dynamic signature of the Bragg glass. Clearly more work is needed, both theoretical and experimental, in order to make progress on the transient solutions when one quickly applies an external current to a superconductor.

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